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Multi-Class Pesticide Residues in Foods, their Chemistry, Prevalence, Determination and Toxicological Aspects; A Narrative Review

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Pesticides are being used abruptly around the globe to combat pest attacks on food produce but if used above permissible level, are not without health risk. Current review clarifies the prevalence of various chemical classes of pesticides on fruits and vegetables to create awareness regarding use and chemistry of each active ingredient. Fourteen most prevalent pesticide classes have been discussed with their entry in market, chemistry, application, spectrum either broad or selective and innovation regarding application. Moreover, various modern and classical analytical methods have also been reported for single and multi-class residues. However, safety limits and possible health impact of the residues have been explicated accordingly to give an introductory note for safeguarding human health. The outcome of current review demands proper surveillance and monitoring of residues from foods in order to have liaison with regulatory bodies to save health and produce. Moreover, various regulatory bodies like Food and Drug Administration, Codex Alimentarius Commission, European Union pesticides databases are quite helpful to monitor and know MRLs (maximum residual limits) of pesticide active ingredients to avoid health related effects. Purposely, futuristic approaches are needed to avoid pesticides over use and subsequent toxicity.
Keywords*:* Pesticide classes, Fruits and Vegetables, Health issues, MRLs, Regulator bodies.

INTRODUCTION

***Multiclass Pesticide Residues*:** Various pesticides are applied on agri-produce to increase yield and reduce pests which affect the crops at one and economy on the other end. According to Food and Agriculture Organization (FAO), globally pesticide usage has reached 4.1 million tons in 2019. However, developing nations are becoming more victim of increased usage of pesticides owing to agricultural extension and emerging pests. Various regions of globe like USA, Europe, Africa, Asia and Australia are although adopting various regulations and strategies to avoid extensive use yet globally, pesticide application is on the rise. These pesticides belong to various chemical classes as types of food commodities and types of pests dictate their application e.g., staple crops as in case of South East Asia is rice so population may be exposure to pesticides which are pertinent to particular types of pests, types of food and type of chemical class. Similarly, 62% of Pakistani rice while 85% Western countries fruits, vegetables, pulses and berries are contaminated with pesticides. Nonetheless, chemical residues on 2-4% domestic foods in China, New Zealand, USA and Europe is above safety limits. There are various regulatory bodies like EFSA, EPA, Codex Alimentarius Commission, which are functional for setting MRLs. However, MRLs are varied according to regions but CAC has worked to harmonize global pesticides MRLs based on JMPR (joint meeting on pesticide residues) by focusing on experimental data. Some regions have more strict regulations while others have less so harmonized standards will be conducive for trade as well as for safety but significant challenges include risk assessment methodologies, regulatory mechanism, agricultural practices and dietary pattern diversification (Ambrus, Yang et al. 2016, Blundo-Canto, Kangogo et al. 2025, Tang, Zhou, et al. 2025).

***Organophosphates*:** Organophosphorus is a chemical group being broadly applied on food commodities. Firstly, introduced OP pesticide (Fig 1) was developed in 1942 i.e., Hexaethyl tetra phosphate that was used as insect killer in agriculture. Various fungicides, herbicides and insecticides may belong to OPs (Table 1a) category and are commercially available. Paraoxon, Monocrotophos, Chlorpyrifos,

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Malathion and Parathion are typical examples of OP pesticides (Sanchez-Santed et al., 2016). OPs are applied on different food commodities to combat various pests and improve yield. Recently according to a meta-analysis on OP pesticides in fruits and vegetables, it was reported that mostly countries complied with the international (CAC) as well as national standards but 32% of samples were exceeding standard limits of OP pesticides, demanding the need for more exploration to address the safety issues (Li, Chen et al. 2023).

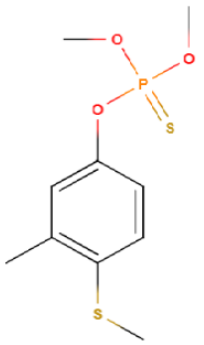

Figure 1. Organophosphates (a representative Fenthion)

***Organochlorines*:** OCPs are probably considered the first developed pesticides for food crops. Moreover, they are resident in environment and stay there but are being used abruptly to control insects (Zacharia, 2011). Despite the ban in 1970s and 1980s, they are still being used and pollute the environment (Vlatanescu et al., 2010). OCS (Table 1a) residues have been studied in various agricultural products including fruits and vegetables for residual effects and fate (Zawiyah et al., 2007). The prevalence of OCs (Fig 2) in fruits and vegetables demand rigorous toxicity level testing to avoid health dilemmas. Recently, a team of researchers reported that OCPs accumulates in food chain because livestock whose meat and bone meal is applied as fertilizer has a potential to contaminate the growing crops as they reported about maize grains which were treated with MBM. Hence, OCPs should be monitored in agricultural produce specifically treated with MBM (Stępień et al. 2025).

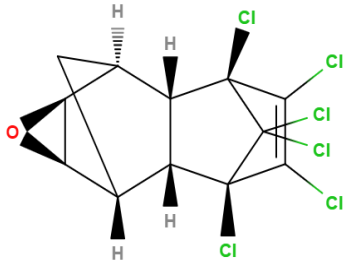

Figure 2. Organochlorine (a representative Endrin)

***Carbamates*:** Carbamates (Table 1a) were developed in 1950's after organophosphates to alleviate various pests worldwide, and 20 types of them are now on the market, with still increasing in diversity. Firstly these were extracted from calabar beans (*Physostigma veneosum*) and owing to their insecticidal activity, were formulated and commercialized (Jiang et al., 2013; Perry et al., 2013; Kumari et al., 2014; Passananti et al., 2014; Leao et al., 2015). Presently a study by (Morsi et al,. 2024) reported that 14 carbamate pesticides (Fig 3) were prevalent on date samples, where most of them were below MRLs, but 21 samples were contaminated with carbosulfan residues surpassing MRLs. Nonetheless, observance of safety limits is quite crucial to save the consumer from health effects.

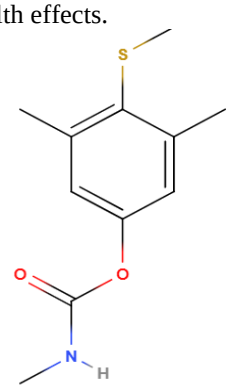

Figure 3. Carbamates (a representative Methiocarb)

***Preythroids*:** Pyrethrum term denotes powdered or dried floral parts of *Chrysanthemum cineum* and *Chrysanthemum cinerariaefolium* from which preythrins are prepared. So in order to augment the capacity of natural preythrins, pyerethroids (Table 1a) were made synthetically from them. They entered in the market firstly in 1952 with launching of Allethrin to abolish household pests. Currently, Preythroids are widely being used for pest management in agriculture in the world pertaining 1000 insect killing chemicals (Thatheyus and Selvam, 2013). Biosensors and non-thermal processing technologies are examples of novel tools that show promise for mitigation and monitoring preythroids. Standardization, matrix interference, and the lack of data on long-term low-dose exposure continue to be obstacles despite advancements (Qi and Zhao, 2025).

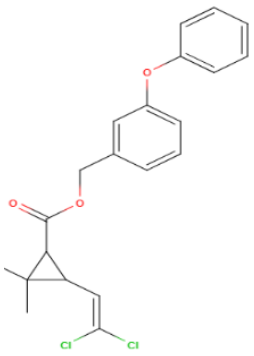

Figure 4. Preythroids (a representative Permethrin)

***Azole*:** Azole (Fig 5) is a unique chemical class of heterocyclic compounds having medicinal as well as pest killing effect. Triadimefon and Imazalil were firstly introduced in market in 1970's for agricultural use to combat pests. These (Table 1a) are being applied widely on food crops and are systemic in action with significant share in fungicide market (Singhal et al., 2011; Cools et al., 2013). However, recent investigations have found the presence of azole and triazole fungicide residues in crops from several nations, occasionally exceeding the specified Maximum Residue Limits (MRLs) imposed by the European Union (Bunquin et al., 2025).

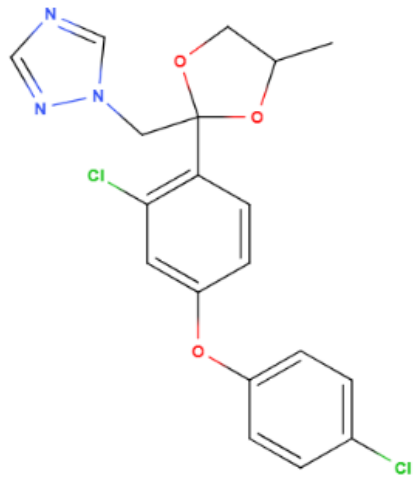

Figure 5. Azole (a representative Difenconazole).

***Neonicotinoids*:** Neonicotinoids (Fig 6) form a main chemical class of pesticides derived from naturally occurring alkaloid and toxin, nicotine. NNTs (Table 1a) stepped in the market with Imidacloprid as first product in 1990's. Since their launching, many new compounds of this class have been developed and commercialized for various crops to eradicate pests (Sanchez-Bayo et al., 2016). Neonicotinoids are mainly used as insecticides although some members are both fungicides and insecticides, they are widely being applied on food crops and have systemic action with broad pest killing potential (Chen et al., 2014). Metabolites (m-NEOs) are just as harmful to the human body as their parent neonicotinoids (p-NEOs), if not more so. Nevertheless, research on m-NEOs in fruits and vegetables is still limited (Chen et al., 2025).

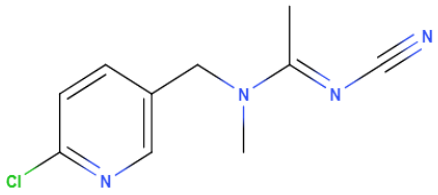

Figure 6. Neonicotinoids (a representative Acetamiprid)

***Benzoyl Ureas*:** Benzoyl Ureas (Table 1a) are chemicals belonging to Ureas pesticides which have urea as common basic structural moiety. Particular application, structural moieties and functionality dictates the types of UPs to be applied on fruits or vegetables. Mostly, UPs are colorless, odorless and can be dissolved in water or organic solvent easily. Bus (Fig 7) pesticides are mainly applied as insecticide due to interference with growth stages of insects (Shukla and Kulshretha, 1998; Nollet, 2004; Nollet and Toldra, 2012). BUs were introduced for application in 1970's and since then many compounds related to this category have been developed for alleviating crop pests (Kamrin, 1997). The effects of pesticide residues especially of BUs on health have been the subject of several studies and evaluations by the World Health Organization (WHO). They stress that eating food contaminated with low amounts of pesticide residues over an extended period of time can have negative impacts on human health, including neurological, reproductive, and carcinogenic effects (Jan et al., 2025).

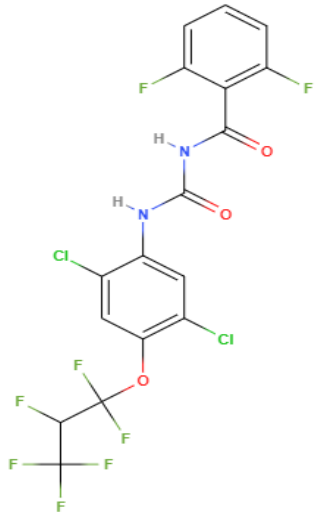

Figure 7. Benzoyl Ureas (a representative Lufenuron)

***Spinosyns*:** Spinosyns (Table 1b) constitute a unique family of macro cyclic lactones derived from fermentation by soil residing two bacterial strains of species namely *saccharopolyspora* belonging to *actinomycetes* genus. Spinosad was introduced in agrochemical market during 1997 and proved an important milestone towards development of various compounds of this category. Presently, according to some reviews 20 or 24 types of Spinosyns (Fig 8) and 800 semi synthetic analogues have developed and characterized (Brooks and Roberts, 1999; Thompson et al., 2000; Sparks et al., 2001; Gilbert and Gill, 2010; Mani et al., 2013). The effects of pesticide residues on health have been the subject of several studies and evaluations by the World Health Organization (WHO) demanding more awareness and safe application.

Table 1a. Multiclass residues with structural description and typical variants.

Chemical Class of Pesticide	Structural Description	Examples	Reference
Organophosphates	OPs chemically consist of phosphoric acid and its derivatives. Structurally they have Phosphorus at center and thiophosphoric bond or Functional phosphoric.	1. Chlorpyrifos 2. Malathion 3. Parathion, 4. Fenthion	(Elersek and Filipic, 2011; Kazemi et al., 2012)
Organochlorine	Organochlorine pesticides contain five or more Cl atoms as chemical moieties in their structure. Organochlorine pesticides depict cyclic aromatic ring and aliphatic chains in their structure.	1. Endosulfan 2. Endrin	(Kang and Chang, 2011)
Carbamates	Urethane is their functional group (R1R2NCOOR3) where R1=hydrogen, R2=small chain alkyls and R3=oxime, phenol or unsaturated hydrocarbons. Location of R1 and R2 dictates selection of Carbamates for particular insect pest	1. Methiocarb 2. Ethiofencarb 3. Furathiocarb	(Sanchez-Brunete et al., 2003; Lin et al., 2010; Perry et al., 2013; Jiang et al., 2013; Kumari et al., 2014; Passananti et al., 2014; Leao et al., 2015)
Preythroids	Pyrethrins contain Chrysanthemic acid, Pyrethric acid and 2 carboxylic acids in ester constituency. They are further categorized into Type-I (not having alph-cyano group) and type-II (having alpha-cyano group)	1. Cypermethrin 2. Deltamethrin 3. Permethrin	(Laskowski, 2002; Schleier and Peterson, 2011; Palmquist et al., 2012; Rehman et al., 2014)
Azole	The chemical structure contains five membered aromatic azole ring comprising nitrogen atoms and one non-carbon atom i.e. sulphur, nitrogen or oxygen.	1. Fenbuconazole 2. Tebuconazole 3. difenoconazole	(Khalil and Huat, 2013 ;Zhang et al., 2014)
Neonicotinoids	Their structure mainly constitutes four parts (i)A bridge chain (ii) Heterocyclic group (iii) Reactive group and (iv) Nitrogen containing ring structure	1.Acetamiprid 2. Imidacloprid 3. Thiamethoxam	(Jeschke et al., 2010; Quinn et al., 2011; Haibo et al., 2016; Wood and Goulson, 2017)
Benzoyl Ureas	Depending upon nature of substituents UPs are classified as Phenyl Urea Pesticides, Benzoyl Urea pesticides, Thiourea pesticides and Sulfonyl Urea pesticides.	1. Chlorfuazuron 2. Lufenuron 3. Hexaflumuron	(Sannino and Bandini, 2005; Quinn et al., 2011;Kim et al., 2013).

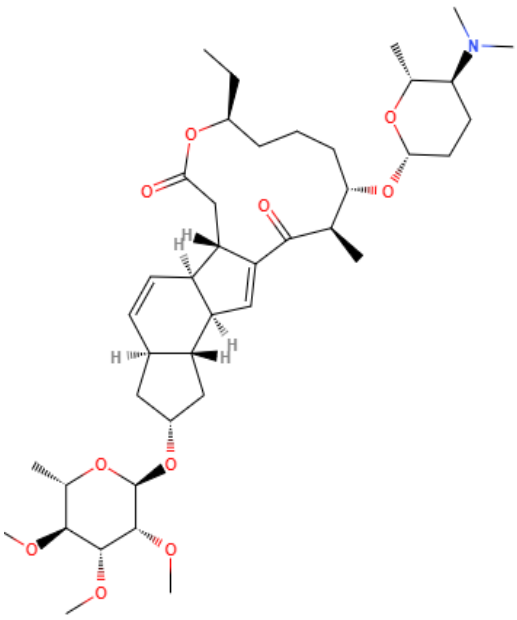

Figure 8. Spinosyns (a representative Spinosad).

***Strobilurins*:** Strobilurins (Table 1b) comprise a novel chemical class of fungicides developed and characterized after the isolation of natural analogues, strobilurin-A and strobilurin-B from a wild fungus *Strobilurus tenacellus* of *Basidiomycete* species. Nomenclature of Strobilurins (Fig 9) follows their order of discovery that is A, B, C etc. Many synthetic analogues of this family have been developed to cope with fungi attack on food crops (Grabley and Thiericke, 1998; Kroib and Steglich, 2004; Balba, 2007; Huang et al., 2007; Bag et al., 2016; Basak et al., 2016). These entered in the market firstly in 1996 and from then till now enormous number of related compounds have been synthesized and commercialized. Along with HPLC and GC-MS, different novel techniques are being used for its detection but due to complex food matrices and different sample preparation methods, the reliability of results is limited (Yang et al., 2023).

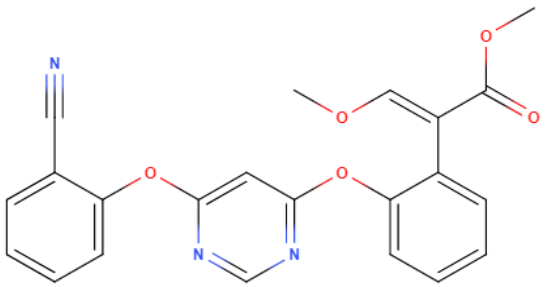

Figure 9. Strobilurins (a representative Azoxystrobin).

Table 1b. Multiclass residues with structural description and typical variants.

Chemical Class of Pesticide	Structural Description	Examples	Reference
Spinosyns	The core structure comprises polyketide derived tetracyclic ring that is substituted at C-17 and C-9 with amino sugar and neutral sugar respectively.	1. Spinosad	(Crouse et al., 2001; Stebbins et al., 2002; Kirst, 2010; Lopez et al., 2011)
Strobilurins	The common structural element of this category is β-Methoxyacrylate having three features i.e. toxophore, central nuclear structure and side chain	1. Picoxystrobin, 2. Pyraclostrobin 3. Azoxystrobin	(Bartett et al., 2001; Bartlett et al., 2002; Heinemann et al., 2004; Sridhara et al., 2011; Kolosova et al., 2017)
Cyano-acetamides	These are bifunctional compounds containing cyano and carbonyl moieties with heterocyclic structure making them unique	1. Cymoxanil	(Schwartz et al., 1967; Fadda et al., 2008; Darwish et al., 2014; Fouad, 2014; Rauf et al., 2015; Abdel-Latif et al., 2017)
Macrocyclic Lactones	Structurally MLs contain complex rings which are called macrolides	1. Ivermectin 2. Abamectin	(Danaher et al., 2006; Nakao et al., 2015; Pimentel-Trapero et al., 2016; Ross, 2017).
Mandelamides	These chemicals have a mandelic acid moiety which is alpha-hydroxybenzene acetic acid.	1. Mandipropamid	(Cederbaum et al., 2004; Lamberth et al., 2006; Schirmer et al., 2012; Prydderch et al., 2017)
Substituted Aromatics	Benzene has a basic ring structure which can be substituted by suitable functional group to form specific compounds like pesticides or pharmaceuticals.	1. Chlorothalonil 2. Dicloran 3. Chloroneb	(Frangos et al., 2016; Martinez-Lopez et al., 2017).
Oxidiazines	This class has heterocyclic structure containing N-N-C-O or N-N-O inside a 6 membered ring and organic synthesis is an exclusive way to synthesize them. Anyhow natural Oxidiazines includes nocuolin-A whose chemical structure comprises 1, 2, 3-oxadiazine	1. Indoxacarb	(Voracova et al., 2017).

***Cyano-acetamides*:** Cyano-acetamides (Fig 10) is a chemical class of compounds having multipurpose background with antifungal being the most important being applied in treatment of crop fungal diseases. These compounds are synthesized in a numerous way depending upon particular pharmacological or agricultural use. These (Table 1b) possess highly reactive intermediates namely phenyl-4,5,6-trimethyl-3-cyano-2- pyridines and phenyl-4,6-dimethyl-3- cyano-2-pyridones which confer them with ability to have biological functionality (Schwartz et al., 1967; Fadda et al., 2008; Fouad, 2014; Rauf et al., 2015; Abdel-Latif et al., 2017). They revolutionized the market 1976 with the launch of Cymoxanil a cyano-acetamide oxime and systemic fungicide particularly against oomycetes fungi (Lebeda et al., 2008; Morton and Staub, 2008; Sharma, 2014; Pohanish, 2014).Grape barriers, oranges and lettuce are sprayed with cyano-acetamides i.e. Cymoxanil alongwith other pesticides to alleviate fungal infections (Cherton et al., 1991; Cohen and Gisi, 1993; Kai et al., 1998; Lehotay *et al.*, 2005; Liu et al., 2009; TP et al., 2015; Pena et al., 2017). Acetamiprid low soil retention raises concerns regarding its environmental fate because it can enter environmental compartments and perhaps enter the food chain through aquatic life (Liu et al., 2025).

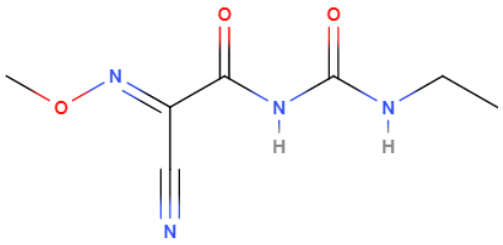

Figure 10. Cyano-acetamides (a representative Cymoxanil).

***Macro cyclic Lactones*:** MLs (Fig 11) comprise a promising class of compounds i.e. Milbemycins, Avermectins and Spinosyns with each of them contains a huge array of chemicals. MLs are fermentation products owing to the activities of soil dwelling *actinomycetes* belonging to genus *streptomyces*. These (Table 1b) are not only used as anti-parasitic agents but also for agro-ecosystems to eradicate crop damaging pests (Molinari et al., 2010; Lumaret et al., 2012; Jacobs and Scholtz, 2015; Kay et al., 2016). Milbemycins are reported as first members of this insecticide class came in limelight at 1970's while Ivermectin was launched in 1981.Grapes and date fruits are sprayed with MLs in order to

combat various pests e.g. arthropods or even nematodes etc (Wrigley and Chemistry, 2000; Lesueur et al., 2008; Kamel et al., 2010; El-Saeid and Al-Dosari, 2010; Campbell, 2012). Because they are frequently employed in food-producing animals as antiparasitic medications, their lipophilic qualities and extended persistence in animal tissues may result in residues in edible products if appropriate withdrawal periods are not followed following treatment (Mesfin et al., 2024).

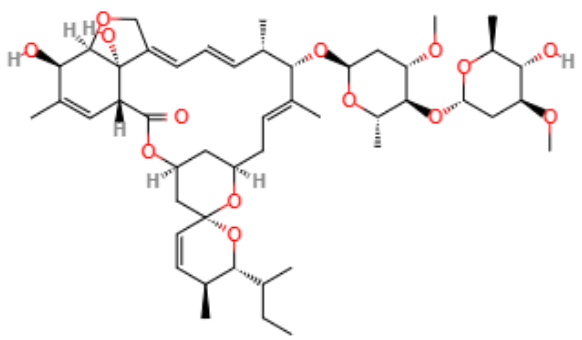

Figure 11. Macrocyclic Lactones (a representative Abamectin)

***Mandelamides*:** Mandelamides (Fig 12) constitute an important class of agrochemical having excellent ability to eliminate menace of oomycetes specially *Plasmopara viticola* and *Phytophthora infestans*. The Amine component of mandelic acid is 2-phenethylamine which can be synthesized by many routes to compile into Mandelamides (Table 1b) (Cederbaum et al., 2004; Lamberth et al., 2006; Schirmer et al., 2012; Prydderch et al., 2017). Mandipropamid is an important member of Mandelamide class and was launched in 2005, after receiving registration firstly in Austria. Since then it was introduced in numerous countries as a sole or combined with other active ingredients (Cohen et al., 2007; Schirmer et al., 2012; Hayes and Kruger, 2014). Oomycetes family of fungi is very dangerous for food crops and historic records revealed famines and serious economic losses owing to infestation of its strains. Grape berries and vegetables are susceptible to fungal attack and this issue is addressed by farmers by applying Mandelamides alone or in combination with other agro-chemicals (Lamberth et al., 2008; Mazzini, 2009; Blum et al., 2010; Malhat and Mahmoud, 2012; Gonzalez-Alvarez et al., 2012; Noguerol-Pato et al., 2014; Zhang et al., 2014; Nanni et al., 2016). In 2025, national agencies and regulatory organizations such as the European Food Safety Authority (EFSA) have concentrated on monitoring chemical residues in animal products and establishing MRLs for agricultural pesticides (Huang et al., 2025).

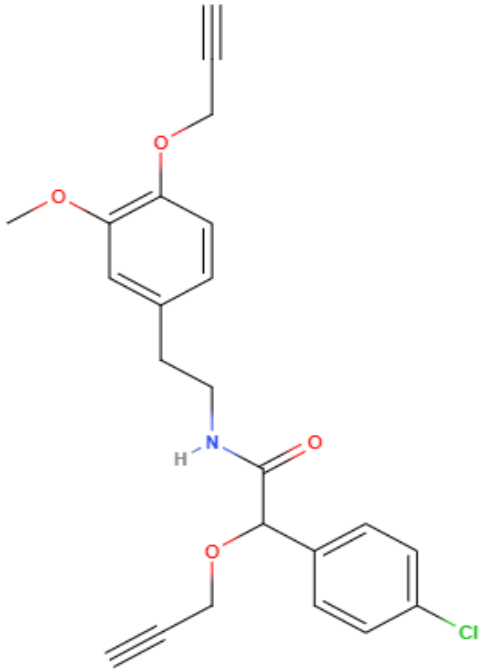

Figure 12. Mandelamides (a representative Mandipropamid)

Substituted Aromatics: Some compounds of this category include pentachloro-nitrobenzebe (PCNB) (Fig 13) which were used as foliage protectant since 1930s, while pentachlorophenol was used as herbicide and for seed treatment starting from 1936. Moreover, for cereal crop (wheat), Hexachloro-benzene came on limelight in 1945. Chlorothalonil is another member of this family having broad potential to act as fungicide and was introduced in 1964. In 1965, Chloroneb was developed and applied for turf and cotton disease management. Dicloran is another substituted aromatic fungicide being using to control various fungi like *botrytis, rhizopus* and *sclrotinia* on food crops (Matolcsy et al., 1989; Spencer-Phillips et al., 2002; Mishra, 2009). Fruits like grapes and vegetables like cabbage being susceptible to fungus attack are sprayed with substituted benzene pesticides (Table 1b) to save the vineyards (Northover and Ripley, 1980; Brophy and Laing, 1992; Leroux et al., 1999; Korolev et al., 2011; Satpathy et al., 2014; Meghesan-Breja et al., 2015). In contrast to conventional techniques, Raman spectroscopy and other similar advanced techniques allow non-destructive, quick, and *in situ* analytical capabilities which are changing the face of PCNB detection (Wang et al., 2025).

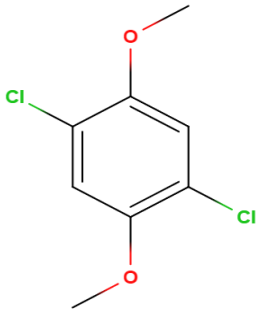

Figure 13. Substituted Aromatics (a representative Chloroneb)

***Oxidiazines*:** Oxidiazines (Fig 14) is a chemical class of compounds possessing biological and chemical attributes. Discovery of representative i.e., Indoxacarb (Avaunt, Steward®) a Pyrazoline type broad range insecticide, was due to evolution of Pyrazoline moiety via pyridazines analogues, initially recognized in 1972 (McCann et al., 2001; Pedigo and Rice, 2014). Oxidiazines have a wide potential as agrochemicals because of their heterocyclic chemistry and pest eradication ability. Grape berry and vegetables (cabbage) is attacked by different insects and causing yield loss and produce deterioration, hence, various agrochemicals having pest killing perspective are applied during preharvest interval or even after harvest in some rare cases. Oxidiazines (Table 1b) are fatal for lepidopteron insects and eliminates them quickly (Fauziah *et al.*, 2012; Souza et al., 2016; Hasan, 2016). In some fruits, such as apples, indoxacarb exhibits quick initial sorption into the cuticle but delayed desorption into the fruit tissue, which affects residue levels and persistence. For an insecticide to be effective against pests, ingestion is a crucial point of entry (McCann et al., 2025).

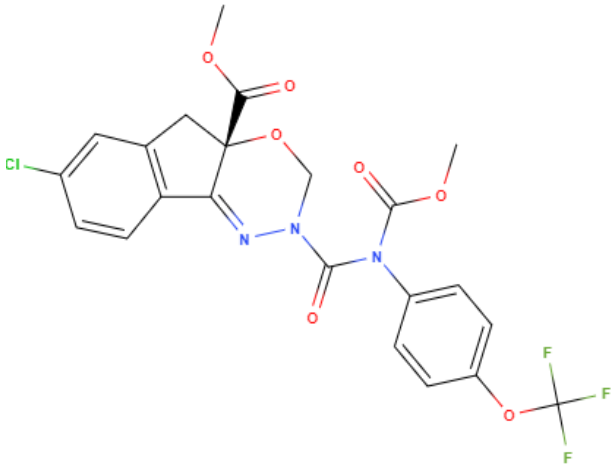

Figure 14. Oxidiazines (a representative Indoxacarb)

***Review Methodology*:** Review was compiled by authors by searching from various databases like PubMed, NCBI, NIH, Google Scholar, Science Direct, WOS and related ones. Articles were searched using terms and keywords like "pesticides classes", "pesticides chemistry", "analytical methods of pesticides'," toxicity of chemical residues", "maximum residues limits of pesticides" from various databases. Inclusion criteria included only published relevant research, review and meta-analyses and in english language while unpublished, incomplete and irrelevant were excluded. Authors reported only research articles from last 25 years to have thorough understanding of diverse chemical residues. Approximately 170 research publications were reported here out of 400, remaining were not reported as those were least relevant or duplicates and not fulfilling the review contents.

***Multiclass pesticide analytical methods*:** Pesticides are screened from various fruits and vegetables using mostly applied techniques HPLC and GC but advancement in analytical instruments gave birth to excellent methods having good sensitivity and reliability. Earlier, (Wang et al., 2015) fabricated microfluidic device equipped with colorimeteric detection for Malathion on basis of acetyl cholinesterase inhibition, which is a great innovation. Similarly, molecular imprinted polymers (MIPs) are also excellent for detection of pesticides from an array of complex matrices where MIPs act as discriminatory for organophosphates and other pesticides making their detection possible (Boulanouar et al., 2018). Owing to burning issues of pesticides and food safety various novel pesticide tracing methods have become evident *e.g.*, multiwall based carbon nanotubes having excellent electrochemical detection were reported by (Xu et al., 2017). Contemporarily, graphene-modified based boron doped with diamond electrode method has been explicated by (Pop et al., 2017) for Carbaryl and Paraquat due to demand of reliable and sensitive method for analysis from food, water and environment samples in order to ease monitoring and cope with health issues. Spectroscopic techniques are also promising among the pesticide analysis in Egypt where pesticides namely (Metalaxyl, Mandipropamid, Carbendazim, Thiophenate Methyl) have been determined by (Hegazy et al., 2018) from cucumber. Presently, researchers reported a unique isotope based specific compound analysis of pesticides from large water bodies or water from greater volumes where a typical extraction of herbicides has been reported by (Torrento et al., 2019) who used gas chromatography-isotope ratio mass spectrometry. Moreover, pesticides (Metribuzin, Atrazine, Paraquat and Imazaquin) from water have also been determined by applying conducting polymers using sensors made up of humic, polyaniline and lignin materials(Medeiros et al., 2005).

Fruits and vegetables are being analyzed using ELISA-Kits for determination of pesticides as (Yamasaki et al., 2015) explicated five kits specific for following pesticides

(Azoxystrobin, Acetamiprid, Imidacloprid, Fenitrothion and Chlorothalonil) which depicted excellent results. Moreover, (Bucur et al., 2018) elucidated that diverse class pesticides (Dithiocarbamates, Carbamates, Triazines, Phenols, Diazines, Phenylureas, Organophosphates) can easily be determined by applying enzyme based biosensor technology which is again a new, reliable and targeted method. Previously, (Gamiz-Gracia et al., 2005) explicated that chemiluminscence based pesticide detection is also feasible for liquid phase samples. Currently among the astonishing analytical technique for pesticide detection is a hyper spectral imaging which was applied by (Zhan-qi et al., 2018) on spinach for Dimethoate determination and results were satisfactory. Nonetheless, Dinotefuran from cucumber and various soil samples has been determined by using potentiometric devices having incorporated molecular imprinted polymers. Likewise another innovation in pesticide analysis include use of hanging mercury drop electrode by utilizing square wave voltametery from river water (dos Santos et al., 2004).In similar duration reported clay modified electrode for pollutants including Endosulfan detection. Later, (Jaffrezic-Renault and Dzyadevych, 2008) reported conductimeteric and micro-biosensor based devices for pesticides monitoring in environmental samples. Furthermore, hyphenated techniques like HPLC-API-MS (high performance liquid chromatography atmospheric pressure ionization mass spectrometry), API-MS and HPLC-DAD (high performance liquid chromatography diode array detector) are applied vastly on pesticide monitoring from food samples (Bogusz, 1999). Currently, machine learning approaches have been harnessed for enhanced color recognition of test strips based pesticide analysis which works on colorimeteric reaction that is subsequently interpreted for pesticides on fruits and vegetables (Dai, Chen et al. 2025).Furthermore, future innovations include AI driven spectroscopy, imaging analysis, sensor based technologies, Internet of things and block chain and will require a suitable model to provide transparent and reliable outcomes in food safety. Although it is challenging but once optimized will provide unbiased predictions and data privacy as well as integrity (Shehzad et al. 2025). Conclusively, different pesticide detection methods have been discussed but some of them are quite specific and cannot detect even second member of same pesticide class. Likewise, each method has its own limitations and applications like matrix effect, limit of detection from particular food, imaging interferences from colored foods but as a whole HPLC and GC are considered as broad-spectrum analytical approaches.

***Diverse class pesticides toxicological aspects*:** Various pesticides are applied on crops to alleviate pests like rodents, birds, nematodes, insects and weeds. Pesticides are either synthetic or naturally synthesized to achieve desired pest control. But various factors act as driving forces to contaminate environments or dislodge these chemicals when sprayed on commodities i.e. by leaching, rains, erosion and evaporation causing toxicity on non-target organisms (Lushchak *et al.*, 2018). Based on toxicity pesticides are classified into various modules *i.e.*, class I (highly toxic), class II (toxic), class III (moderately toxic), class IV (slightly toxic), class V (virtually non-toxic). Pesticides affect human health negatively as 150,000 people die each year owing to pesticide poisoning. Pesticide exposure can be functional via various pathways like negative effects on immune system, psychological wellbeing, neurological pathways as well as by genotoxicity, memory loss and blood related issues. Pesticide's exposure data also shows various types of cancers, oxidative stress, hormonal disruption and birth defects not only in human but also in animals (Garud et al,. 2024). Currently (Adjei et al., 2025) reported that susceptible groups include older adults, children, pregnant women and sensitive individuals as adverse responses are aggravated upon exposure so dietary as well as occupation exposures need careful attention.

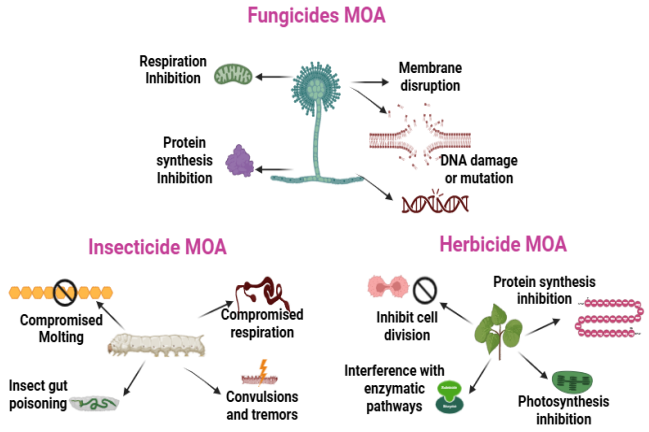

Figure 15. Pesticide Mode of Action

In order to save human health discrepancies knowledge of aforesaid classes and their mode of action is very important. Fig 15 describes their MOAs for various pests while their MOAs for human health are described in previous paragraph. Further mitigation strategies as mentioned in figure 16 should be adopted to lessen the negative health outcomes. Thus, regulator bodies have set MRLs beyond which pesticides elicit not only health issues but also environmental issues affecting non-specific animals and organisms. Moreover, to avoid toxicity by pesticides registration is important step where developer conducts research and submits findings to registration authority who after careful scrutiny and expert opinion accepts or denies the pesticide. This phenomenon of evaluation of pesticides occurs again and again till satisfaction of regulatory body (EU) and final decision is lime lighted (Damalas and Eleftherohorinos, 2011; Liska and Kolesar, 1982). Among the diverse class pesticides pyrethroids, carbamates, organochlorine and

organophosphate tend to accumulate in foods of plant, animal, water and soil origin causing serious health threats like kidney, liver and even cancer in consumers as well as in farmers spraying pesticides. In order to dilute the impact of the synthetic pesticides various natural are being tailored but some of them are even more toxic. Hence quest is long-lasting to develop an ideal agrochemical (Chrustek *et al.*, 2018; Mossa *et al.*, 2018).

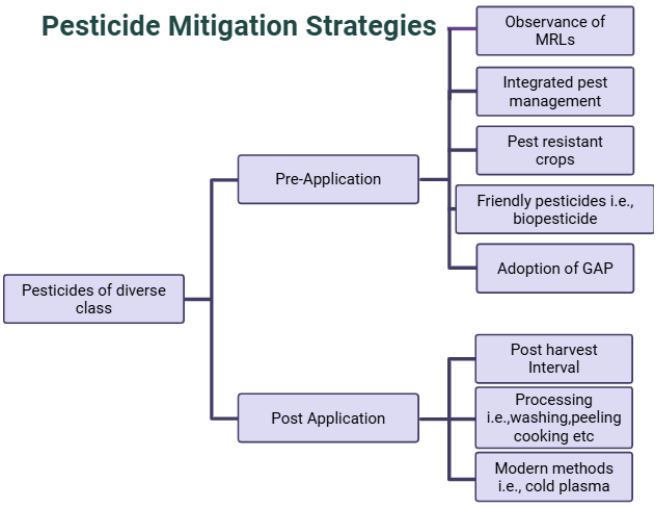

Figure 16. Pesticide Mitigation Strategies

***Conclusion*:** Pesticides are applied around the globe in order to control variety of pests where with increasing resistance of pests, various chemical classes have been developed like OCs, OPs, Carbamates, Oxidiazines, Azols, Mendelamines, Pyrethroids and various others. Some of the pesticides are persistent while some are resilient and vanish quickly after performing their function. Various analytical methods have been reported in this review depending upon type of chemical class or type of pesticides or even multi-residue approaches were reported. Moreover, toxicity classes and toxic effects have been described in current review. Further, regulatory bodies and MRLs have been discussed if they are obeyed one can easily save human beings from health anomalies. Pesticide's prevalence is increasing day by day rendering their scrutiny and alternative an essential research task so that masses can be saved from food and environmental issues.

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***CRediT author statement*:** *Authors conceptualized, compiled and refined the manuscript.*

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Ethical statement*: *N/A

***Availability of data:** Authors have reported the data in current review.*

***Consent to participate*:** N/A

***Informed consent*:** N/A

***Consent for publication*:** *Authors submitted consent to JFPNR journal to publish the current review article.*

***SDGs addressed:** Zero Hunger, Good Health and Well-being.*

***Policy referred*:** International Regulatory Frameworks Governing Multi-Class Pesticide Residues; Codex Alimentarius Commission (CAC) Guidelines on Maximum Residue Limits (MRLs); Joint FAO/WHO Meeting on Pesticide Residues (JMPR): Risk Assessment and Harmonization; Food and Agriculture Organization (FAO) Policies on Sustainable Pesticide Use.

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